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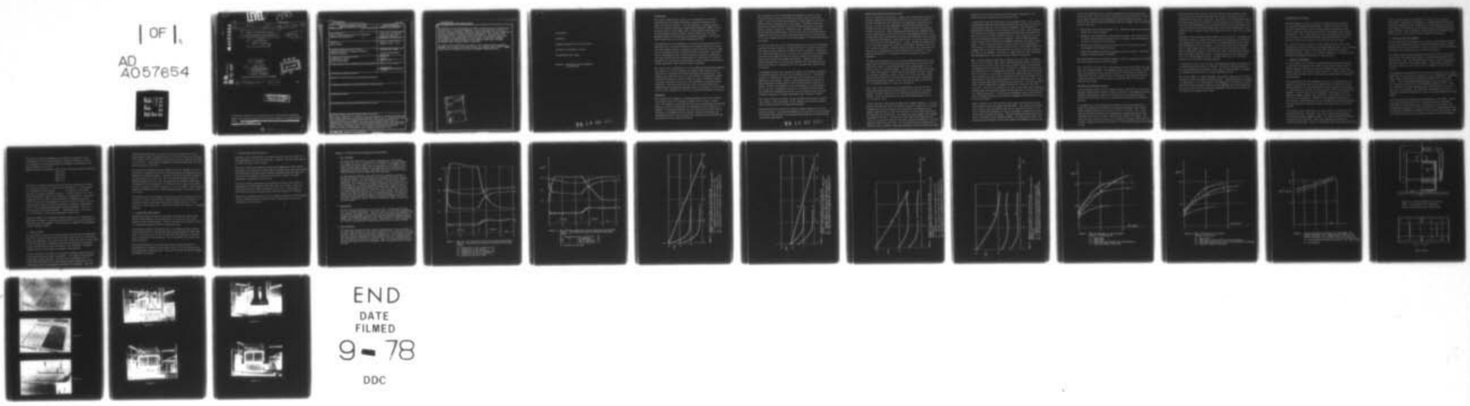

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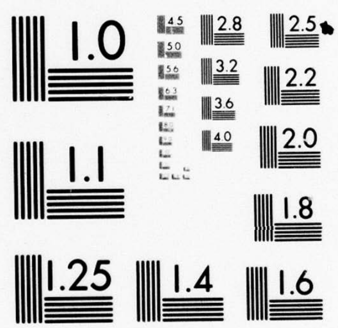

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This report summarizes the results of an investigation to evaluate experimentally the thermal performance of protected membrane roofs under wet weather conditions. The investigation is sponsored jointly by the Cold Regions Research and Engineering Laboratory (CRREL) and the European Research Office (ERO) under the United States Government and by the Norwegian Building Research Institute (NBI) under the Royal Norwegian Council for Scientific and Industrial Research. The Project work was performed at the Trondheim Laboratory of NBI.

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The objective of the investigation has been to measure the heat transmittance characteristics of protected membrane roofs during conditions of rain on the roof, during subsequent evaporative drying conditions, and for comparison, during dry weather, including different wind speeds. The results of the investigation serve to develop design information in parametric form which can be used for the preparation of construction criteria and standards, for planning and design purposes and for computer modelling of thermal performance under varying climatic conditions.

The scope of the investigation has been to test characteristics protected membrane roof sections in an environmental test chamber under defined climatic conditions and recording the thermal performance characteristics.

Introduction

Background

Summary description of test and results

Derivation of parametric results

Recommendation for design

Appendix: Description of test apparatus and procedures

Introduction

This report summarizes the results of an investigation to evaluate experimentally the thermal performance of protected membrane roofs under wet weather conditions. The investigation is sponsored jointly by the Cold Regions Research and Engineering Laboratory (CRREL) and the European Research Office (ERO) under the United States Government and by the Norwegian Building Research Institute (NBI) under the Royal Norwegian Council for Scientific and Industrial Research. The project work is performed at the Trondheim Laboratory of NBI.

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The scope of the investigation is to test characteristic protected membrane roof sections in an environmental test chamber under defined climatic conditions and recording the thermal performance characteristics. The climatic test conditions above the roof include air temperatures between 0 and 20°C at different relative humidities, rain at different temperatures and of different intensities, solar radiation, and different wind conditions. The test results are then used to develop thermal transmittance values for protected membrane roofs as a function of rain, drying, wind and solar radiation, as well as for quiescent conductance conditions.

Background

The characteristic feature of a protected membrane roof is the location of insulation above the waterproof membrane on a low slope, compact roof. The membrane is protected from the severe environmental and physical stresses to which a conventional roof membrane over the insulation is exposed. The protected membrane is at the same time the vapour barrier; therefore, all possibilities of creating a moisture trap between the waterproof membrane on the outside of the conventional roof sandwich and vapor barrier on the inside are avoided.

The insulation in turn is ballasted and shielded by a cover of stone or paving blocks but this cover does not attemp to form a waterproof shield. Rain and meltwater can penetrate it, seep around the insulation boards and flow on the membrane to the drains. A suitable insulating material has characteristics of very low moisture absorption and permeability in order to retain its insulating value. Extruded polystyrene has the desired characteristics. After a rain, the roof can dry again by evaporation while the dew point temperature above the roof is lower than in the roof, because the roof is not sealed against the outside and moisture can escape.

The rain and melt water, while flowing through the roof, and the subsequent evaporative drying, produce a cooling effect which is greater than that of the normal dry heat conduction through the roof or through a conventional roof with the membrane on top. Of course, wet insulation in a conventional roof cannot dry readily and the heat losses through wet insulation are greater than through the original dry material. Therefore, the self-drying characteristic of the protected membrane roof has advantages that must be considered in conjunction with its increased heat losses during wet weather.

In geographical areas with frequent wet weather, the thermal performance of protected membrane roofs must be considered carefully. Off-setting features to compensate for increased heat losses during rain can be incorporated in the design. However, a good understanding of the roof's heat transmittance characteristics under varying weather conditions is needed. Results were reported by some investigators of cooling effects due to rain but no information was given on evaporative drying effects and insufficient information was given on rain cooling effects to permit confident prediction of thermal performance under different climates.

Most parts of Norway are typical coastal climates with periods of significant rainfall. What performance can be expected from protected membrane roofs? What should be the design specifications?

North America has practically all possible climate conditions at one location or another. Are protected membrane roofs suitable for all locations? Can suitable specifications be developed that provide for the needed energy conservation requirements.

Summary description of tests and results

The roof testing was performed in a special roof test apparatus where the climatic conditions on both sides of the test roof could be controlled. Relevant parameters as rain intensity, air temperature, humidity and air velocity, as well as roof temperatures and heat flow,evaporation and drainage from the roof were measured. A typical roof test was generally carried out this way: After temperature equilibrium was established for a certain combination of inside and outside air temperatures and the corresponding heat flow was recorded for the dry roof, artificial rain of outside air temperature was applied. After about 24 hrs. of rain the water was shut off and the roof was left drying for 5 - 7 days. During the drying period air of controlled temperature, humidity and velocity, was drawn across the roof surface and through a condenser where the water which evaporated from the roof was collected and the rate of evaporation was measured. A more detailed description of the apparatus and test procedure is given in Appendix A.

Two model roof structures 2.3 x 1.15 m^2 were tested simultaneously. Both models had a roof deck of 40 mm wood chip boards with a 2 per cent slope. 80 mm thick slabs of extruded polystyrene with straight edges were put directly onto a 1.2 mm PVC membrane. The roof ballast material was either 20 - 50 mm river gravel or 50 mm thick concrete pavers in direct contact with the heat insulation. After a series of 10 tests with these models which had very narrow joints between the polystyrene slabs, some modifications were made with respect to the width and the shape of the joints etc. and another series of 3 tests were carried out.

Fig. 1 and 2 show a typical course of progression of the heat flow and temperature during the wetting period and the first part of the drying period. The rain intensity was 7.5 mm/h.The airvelocity and relative humidity in the air flow across the test roofs during drying were 2.8 - 3.2 m/s and 82 - 90 %.

A short time after rain starts the heat flow increases rapidly to a certain maximum value and then falls off towards a value for steady flow. For given temperatures and rain intensity the maximum value is determined by the dynamic characteristics of the roof structure e.g. the thermal diffusivity and thickness of the roof deck. The steady heat flow depends on the thermal resistance of the deck. The heat flow meter under the ceiling will most likely not measure the true heat flow under transient conditions as this will require an ideal heat flow meter. In the period after the maximum flow is reached, there is however a very good correlation between the heat flow meter

reading and the heat flow computed from the thermal conductance of the roof deck and the temperature drop through the deck.

A comparison of the heat flow curves in the diagrams of Fig. 1 and 2 shows a substantial higher heat flow during the rain period for the test roof with concrete pavers than for the roof with river gravel. The difference is explained by a difference in the draining of the two roofs. Both roofs had very narrow joints between the polystyrene slabs and some water would flow across the top of the slabs towards the drain. This is what occurs in the test roof with gravel where the low impedance to flow through the gravel involves little flow of water on the membrane resulting in a modest cooling effect. With the concrete pavers in direct contact with the polystyrene slabs there is a relatively higher flow resistance in the ballast layer, and a bigger part of the water will penetrate the joints of the heat insulation and flow on the membrane, resulting in a higher heat flow than with gravel. The drainage pattern thus affects the heat transfer during rain.

When the rain stops the heat flow is falling off as the water is drained and the roof is drying. Fig. 3 and 4 show the measured density of heat flow during the first period after rain and the increase in heat flow above the corresponding value of the dry roof. The latter is computed on the basis of the observed air to air temperature difference. After about 20 hrs the heat flow is reduced to a value about 15-20 per cent higher than that of the dry roof, and from this point further drying goes more slowly and depends on the heat transfer to and water vapour transfer from the evaporation zone. This vapour transfer takes place by diffusion and convection. The heat equivalent to the rate of evaporation is higher than the heat flowing into the roof from below. The heat for evaporation of water is also taken from the ballast material where the temperature drops and heat may thus be extracted also from the ambient moving air. In practice the evaporation process will normally also be strongly affected by the radiative exchange of heat between the roof and the environment.

Roofs in practice will most likely not have tight joints between the insulation boards as the roof models described above. The joints will normally have a certain width already from the time of construction either as a result of inaccurate workmanship or from an intentional opening of the joints in an effort to channel the water. The joint width may also increase later due to a shrinkage of the insulation boards. The shape and the width, the positioning and connection of the joints affect the drainage of water as well

as the air permeability of the roof and subsequently the heat transmission through the roof. So do also special features as the application of a filter screen under the gravel or the elevation of pavers from the insulation. To look into this the following modifications were made stepwice with intermediate series of test runs:

1. Opened joints to a width of approx. 3 mm. Applied a filter screen between gravel and insulation boards.
2. Chamfered the bottom edges of the insulation boards. The lower part of the joints thus forming a trapezoidal cross sectional area 10 mm high and 3 resp. 23 mm wide at top and bottom.
3. Elevated the concrete pavers 8 mm from the top of the insulation boards using spacers of extruded polystyrene.
4. Added 20 mm expanded polystyren insulation under the ceiling. Additional thermal resistance approx. 0.6 $m^2{}^oC/w$.

Every modification gave a noticeable change in the heat transmission through the dry roof, during wetting as well as drying.

Fig. 5 and 6 show the heat flow situation after rain for roof models with open joints and chamfered edges, The diagrams in Fig. 3 and 5 and in Fig. 4 and 6 resp. are comparable as they show the results of test which are carried out under almost the same climatic boundary conditions. The drying rate has increased significantly when the joints are opened and that is of course an important achievement.

Derivation of parametric results.

A very important property of all roofing systems is their ability to controll the heat exchange under different climatic conditions. What regards protected membrane roofs special interest is connected with their behaviour during periods with wind and/or rain at low temperatures or when snow is melting on the roof.

As a measure for the relationship between heat loss and rain intensity is chosen the apparent heat transmission coefficient determined under approximately steady conditions at the end of a 24 hrs rain period. Fig. 7 and 8 show the relationship between the computed heat transmittance and the rain intensity for the two roof models with different shape of the joints. The tests have been carried out with an air temperature of approx. 20°C under the ceiling outside air and rain temperature 4 5 °C and wind speed above roof models 2-3 m/s.

A general effect of an opening of the joints between the insulation boards is an increase in the heat transmittance of the dry structures as the air permeability of the roof is increased. This leads to an increased heat flow by convection caused by air infiltration into the joints of the insulation. This is particularly demonstrated in the results from tests on the roof models with 3 mm wide joints with chamfered edges which have a heat transmittance in dry condition which is approx. 25 per cent higher than for the same roof with tight joints.

The effect of open channels during rainfall is more uncertain. At higher rain intensities there is a marked reduction in heat loss which may be contributed to a changed flow pattern where the water is flowing along the joints rather than spreading all over the membrane. In the lower range of rain intensity which is most frequent lack of data prohibits any firm conclusions whether open or tight joints should be preferred. The results from the tests on these small roof models show that there is a strong increase in heat transmission due to air flow through open joints. To what extent this is the same for larger roofs in practice is an open question.

A comparison of curve C and D in Fig. 7 and 8 gives the effect of adding 20 mm of expanded polystyrene under the ceiling. As there is not an unidirectional but very complex heat flow pattern in the roof it is not possible to evaluate by computation what the effect of added insulation will be.

Fig. 9 show change in average evaporation coefficient during the first 24 hrs of drying for the roof models with light joints. Temperature and rel. humidity of outside air is 5-6 °C and 85-90 %. The evaporation is referred to a vapour pressure difference between conditions at the membrane and in the outside air. Open joints seem to give an increased evaporation intensity and a quicker drying without any increased heat losses.

Recommendations for design

Protected membrane roofs have functioned reliably from the standpoint of waterproof protection for many years. However, the fact that the internal cooling effect of water flowing around the insulation boards reduces the thermal efficiency compared with conventional roofs requires consideration. With rising energy costs and the simple need to conserve fuel resources, any unnecessary thermal inefficiency becomes a built-in economic liability and a factor in the choice of the roof design.

The results of the test program show some important design details that influence the thermal efficiency of protected membrane roofs. The following recommendations are mainly concerned with the objective of achieving thermally efficient design. The necessary information to design and build for reliable waterproof performance is taken as given.

1. Channels for drainage.

The bottom edges of the insulation boards should be chamfered (bevelled) or channelled (rectangular) to a width of up to about 12 mm (½ inch) to improve drainage. Rain and meltwater flow remains concentrated in the channels between the boards to a large extent as a result, instead of being pushed under the boards over a large area, thus minimizing the associated cooling effect.

While reducing the wet heat transmittance of the roof significantly, the channels also increase the dry heat transmittance, although to a lesser extend. Therefore, the insulation boards should be placed closely spaced. In actual practice, however, the joints are not tight because installation practice is not the same as in the laboratory and because the boards experience thermal expansion and contraction. Joint widths up to 3 mm 1/8 inch) must be expected. Therefore, the actual heat conductance of the installed insulation boards must be considered to be about 20 % greater than the theoretical conductance based on the conductivity of the board material.

The increase in heat conductance due to the joints is avoided by the use of boards with ship lap joints. The same is achieved by placing two layers of boards with staggered joints. For large insulation thicknesses, two layers may be necessary. Both layers should have chamferred or channelled bottom edges. There is some evidence that the moisture absorption

of the insulation boards is increased as a result of the two-layer construction. Two causes are suspected: A residual water film between the boards impedes the vapor diffusion out of the lower boards into the upper boards, or the skin of the extruded polystyrene boards impedes the vapor diffusion. Until experimental results provide the necessary information, the two layers should be made of equal board thickness.

2. Insulation under the membrane.

The heat transmittance through the roof during wet conditions as a result of water flow through the channels between the boards is governed almost exclusively by the insulating value of the roof materials under the membrane. Therefore, some insulation should be under the membrane.

We recommend that the heat transmittance through the roof during wet conditions (wet heat transmittance) should not exceed the design dry heat transmittance. Thus, the wet weather heat losses of the building will not exceed the capacity of the heating system. On this basis, the required insulating value of the roof part under the membrane is established as follows.

The design heat transmittance of the dry roof is determined by the conductance value of the roof and the design outside air temperature. Recommended design values in Norway are 0.23 W/m^2K (0.04 BTU/h ft^2 ^oF) and -20^oC (-4^oF). The corresponding design conductance value ("U" value) for U.S. Government construction is 0.284 W/m^2K (0.05 BTU/h ft^2 ^oF). Since the conductance values are maximum values, the lower value is valid in both cases as an example. The design heat transmittance of a roof is therefore 9.2 W/m^2 (2.9 BTU/h ft^2), based on an indoor temperature of 20^oC (68^oF).

For wet conditions the design outside temperature is 0^oC (32^oF). Therefore, the "wet conductance" of the roof must not exceed 0.46 W/m^2K (0.08 BTU/h ft^2 ^oF) at full flow. According to our test results, the corresponding conductance of the roof section under the membrane must not exceed about 0.92 W/m^2K (0.16 BTU/h ft^2 ^oF) to achieve this result. That means about 25 % of the roof's insulation should be under the membrane.

This value of 25 % is independent of the amount of insulation chosen (conductance or "U" value) according to the above derivation. However, it is dependent on the design outside air temperature, according to the above derivation, as follows:

Design outside air temperature $\geq$ 0°C; 50 % of insulation under the membrane
-10°C; 33 %
-20°C; 25 %
-30°C; 20 %
-40°C; 17 %

The amount of insulation placed under the membrane should not be so much as to cause the dew point to appear under the membrane. In cold weather it is desirable, even necessary to humidify the air inside buildings for comfort and health reasons. A comfort value of 35 to 40 % relative humidity is used for this analysis, corresponding to a dew point temperature of 5°C (41°F). For an outdoor air temperature of -20°C (-4°F), the dew point is therefore at a level of 15/40 (=0.375) of the insulating value of the roof from the bottom up. Therefore, a maximum of 37.5 % of the insulation may be placed under the membrane. This is 1.5 times as much as the required amount established above. The ratio of 1.5 is applicable to all design temperatures listed above.

During wet weather, the temperature regime through the roof changes from that which is normal in dry weather and the dew point may appear within the insulation under the membrane. This condition is temporary and disappears without noticeable effects.

3. Slope to drain

The evaporative cooling of the roof continues after the rain has stopped and the excess water has drained until the surface water film on the insulation boards has evaporated. Any excess water that cannot drain due to wrong slope of the roof prolongs the evaporation process and associated heat losses. It also increases the moisture absorption of the insulation. Therefore, adequate slope to drain should be provided at the membrane.

On flat, horizontal roof decks it is possible to produce slope to drain by using tapered insulation under the membrane. For example, the following construction appears possible. Based on a heat conductance value of 0.23 W/m²K (0.04 BTU/h ft² °F) and a design outdoor temperature of -20°C (-4°F), about 100 mm of polystyrene insulation are necessary. Under the

membrane there should be an average of 25 mm and a maximum of 37.5 mm. Using tapered boards, a thickness range of 12.5 to 37.5 mm can be utilized. If the taper is 1° or 1% (about 1/8 inch per foot), the length of the slope will be 2.5 m. In this case the spacing of the drains would have to be no more than about 5 m (16 ft).

The insulation thickness above the membrane is 75 mm. Usually it is not necessary to compensate the slope of the membrane and the insulation can be applied with uniform thickness. Therefore, the total insulation thickness will vary from 87.5 to 112.5 mm. Now, the relative thickness under the membrane ranges from 14 to 33 %. Consequently, the thickness range under the membrane can be increased to 5 to 45 mm with 75 mm above the membrane to obtain a relative thickness range of 12.5 to 37.5 % again. The resulting length of the slope is now 4 m and the maximum spacing of the drains about 8 m (26 ft).

The insulation above the membrane should have an actual thickness of 90 mm instead of 75 mm to allow for heat losses through the joint between the insulation boards unless boards with ship lap joints are used. If two layers are chosen, boards with a thickness of 40 mm can be used in a staggered layering.

4. Vented space under pavers.

Elevating the pavers on shims or pedestals or using pavers with an open profile surface against the insulation does not affect the heat transmittance of the roof noticeably. However, there are other reasons in favor of elevating the pavers to create a vented air space.

The moisture retained in the pavers after a rain moves up and out during drying conditions but is driven down again by warm weather and solar radiation. If the pavers are in full contact with the insulation, a moisture stress is imposed on the insulation. This is avoided by the vented space under the pavers.

The heat transmittance of the roof under solar heating conditions is anticipated to be reduced by elevating the pavers. The vented space acts as an additional insulating layer. This is of interest for the hot weather performance of the roof.

5. Filter screen under the gravel.

Placing a filter screen between insulation and gravel does not affect the heat transmittance of the roof noticeably. However, there are other reasons in favour of using a filter screen.

The screen protects the insulation boards from damage due to foot traffic the gravel, from damage due to sharp edges of crushed stone when used instead of round gravel, from displacement by gravel wedging between and under the boards, and from damage in connection with gravel removal for repair, maintenance or modification of the roof.

During hot weather, particularly solar heating conditions, the filter is anticipated to provide thermal protection while wet or damp. This is of interest for the hot weather performance of the roof. In this case, a thick felt-like screen with good water retention properties is desired.

Where this hot weather protection is not needed or desired, a thin and coarse screen is better because the moisture stress effect that it has on the insulation, will be reduced.

Appendix: Description of test apparatus and procedures.

1. Test apparatus

The tests were carried out in a special apparatus for roof testing, cfr. figure 10 - 17. It consists of a thermally well insulated chamber of internal dimensions approx. 2,5 x 2,5 x 2,5 m^2. The chamber is divided into two parts, a lower one for supporting the roof models and in which a certain room climate can be maintained, and an upper part for simulating an external climate. The upper part can be elevated and the lower part pulled out for installation and inspection.

For the protected membrane roof tests two well insulated closed duct-systems were added for recirculation of conditioned air across the top of the roof models. The duct systems were provided with axial fans and dampers for flow controll and thermostatically controlled heaters and condensors for maintaining the desired temperature and dew point of the recirculated air. A special arrangement allowed the condensed water to be collected and from the quantity of condensed water vapour the evaporation during drying could be determined. The roof models were mounted in a steel frame which formed a part of the duct system. When water was applied the frame was open on top. During drying periods the frame was covered with lids of acryllic sheets to prevent exchange of moisture between the recirculated air and the air in the upper chamber which then was used a temperature guard. Water was applied from spray nozzles above the roof models.

2. Measurements

The heat flow was measured over 75 per cent of the ceiling area by eight 0.5 x 0.5 m^2 heat flow meters on each roof model. Air and roof temperatures were measured by thermocouples. During a test heat flow and temperatures were recorded by a datalogger at a varying frequency depending upon the rate of change in the measured quantities. The rain intensity was computed from the steady flow of water through the drains. Measurements of relative humidity, air velocity and quantity of condensed water were taken as spot readings.

3. Test procedures

The tests were carried out with stepwice modifications of the roof models. At every stage a series of tests were carried out with variation of the rain intensity, the air flow and the outside temperature. At appropriate intervals the test work was interupted and the roof models left for a complete drying. Every test series started with a determination of the heat transmittance of the roof models in the initial condition. Then rain was applied for 24 hrs and the roof models dried in the apparatus under controlled conditions about one week.

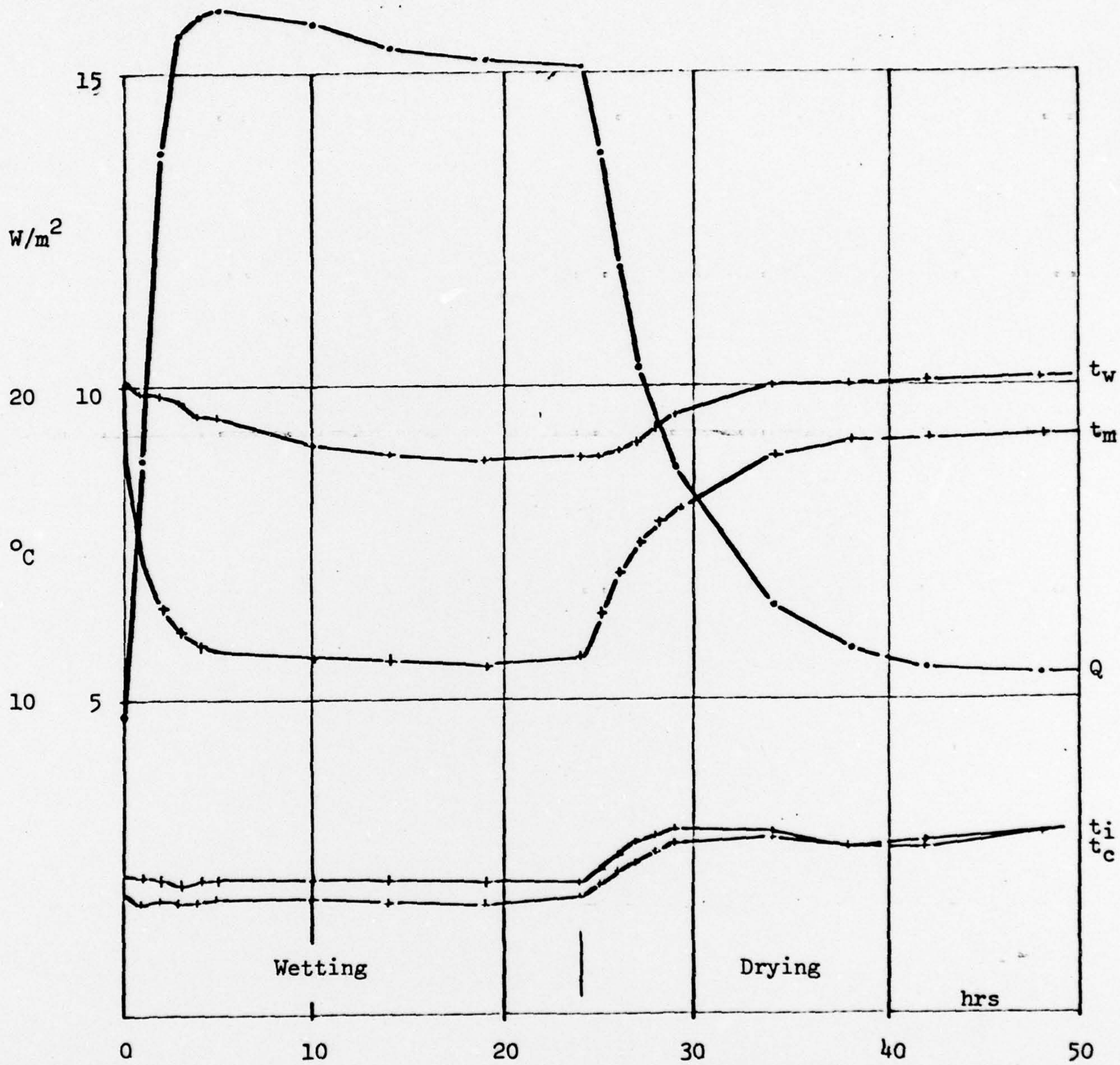


Figure 1. Heat flow and temperatures during wetting and drying period. Ballast: concrete pavers directly on insulation with tight joints.

t_w = temperature of air on warm side, °C
t_m = temperature of the membrane, °C
t_i = temperature of top of insulation, °C
t_c = temperature of air on cold side, °C
Q = density of heat flow, W/m^2

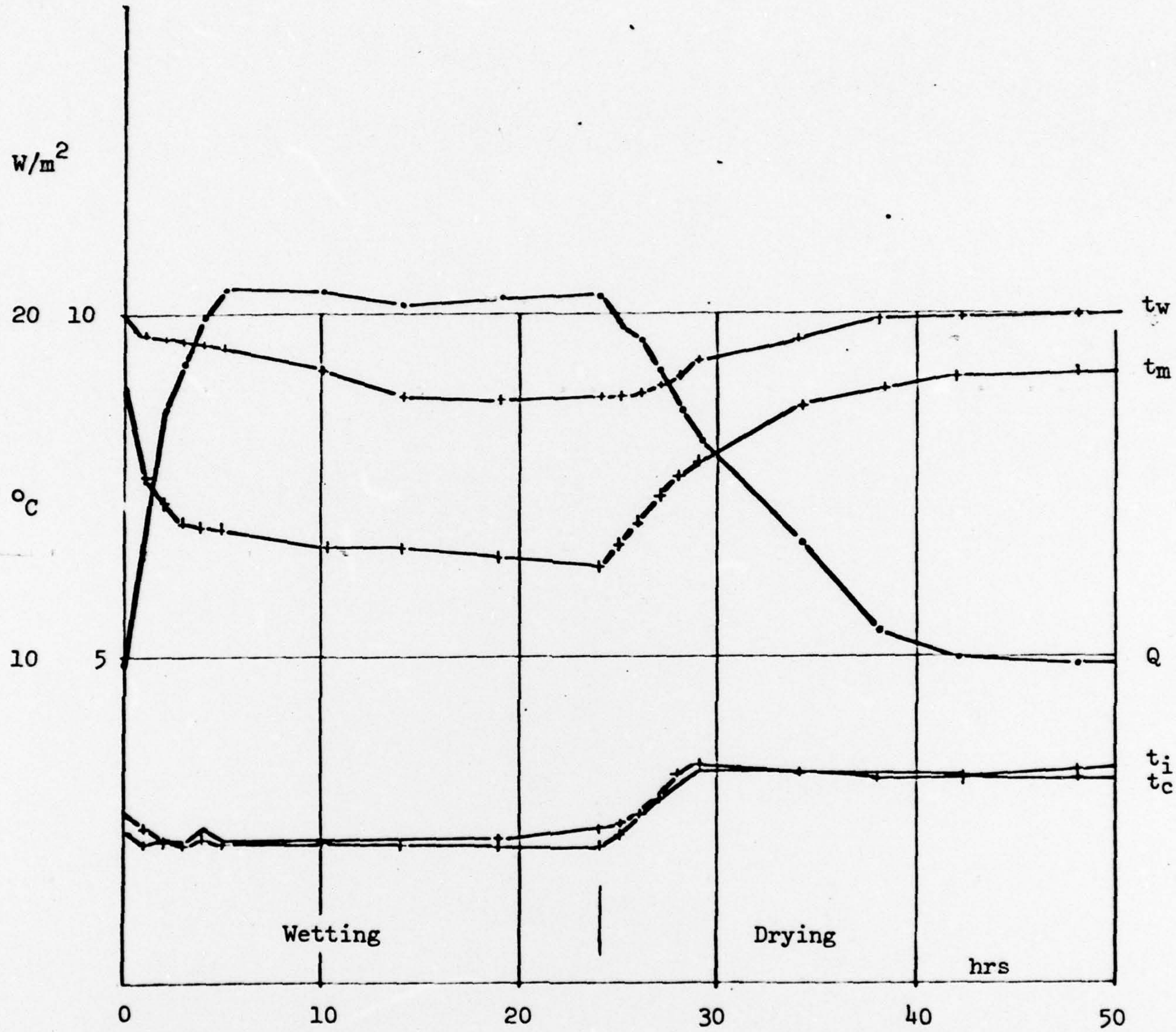


Figure 2. Heat flow and temperatures during wetting and drying period. Ballast: River gravel directly on insulation with tight joints.

t_w = temperature of air on warm side, °C
t_m = " " the membrane, °C
t_i = " " top of insulation, °C
t_c = " " air on cold side, °C
Q = density of heat flow

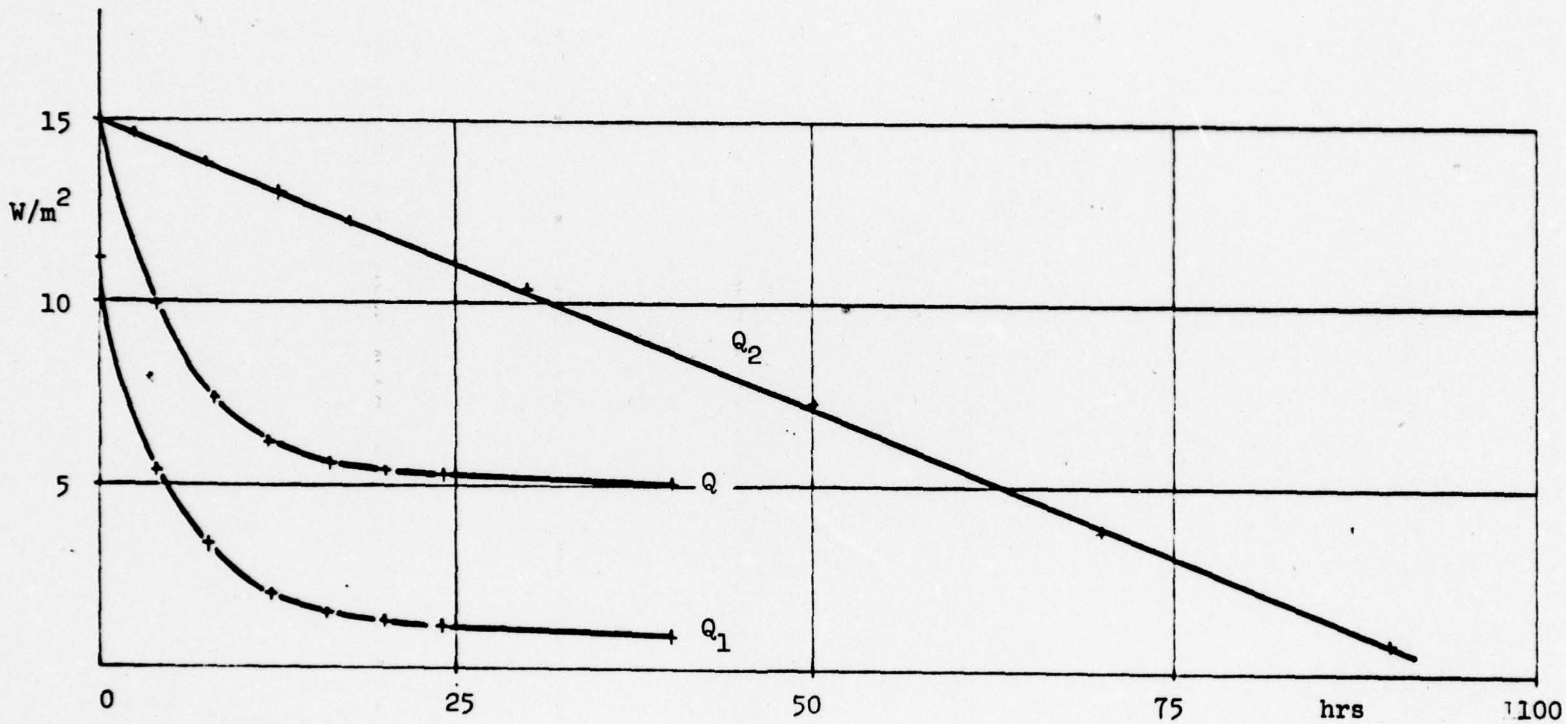


Figure 3. Evaporation heat transfer on the roof after rain.
Ballast: concrete pavers directly on insulation with tight joints.

Q = measured density of heat flow through wet roof, W/m^2

Q_1 = increase in density of heat flow due to moisture, W/m^2

Q_2 = heat equivalent to the measured rate of evaporation, W/m^2

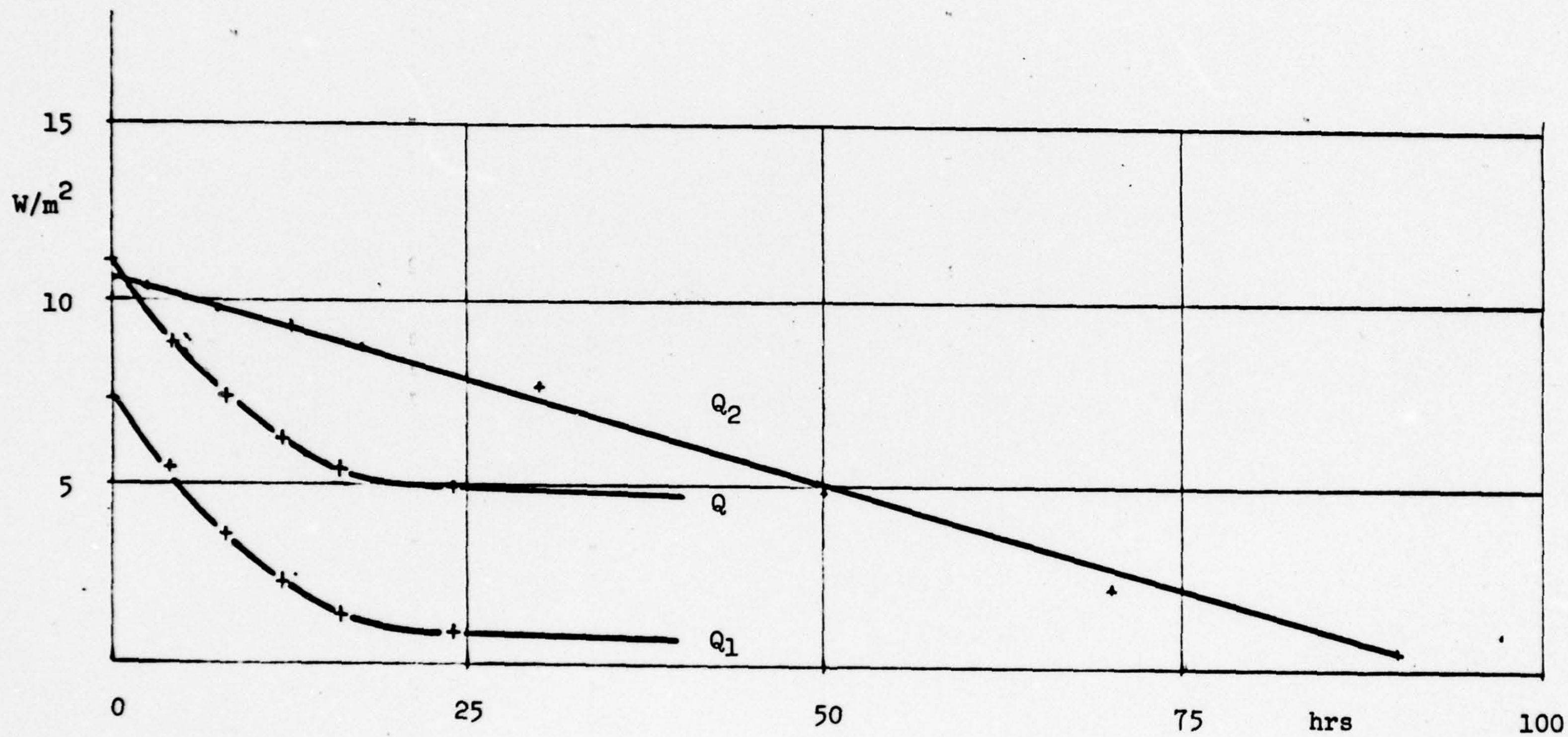


Figure 4 Evaporation heat transfer on the roof after rain.
Ballast: river gravel directly on insulation with tight joints.

Q = measured density of heat flow through wet roof, W/m^2
Q_1 = increase in density of heat flow due to moisture, W/m^2
Q_2 = heat equivalent to the measured rate of evaporation, W/m^2

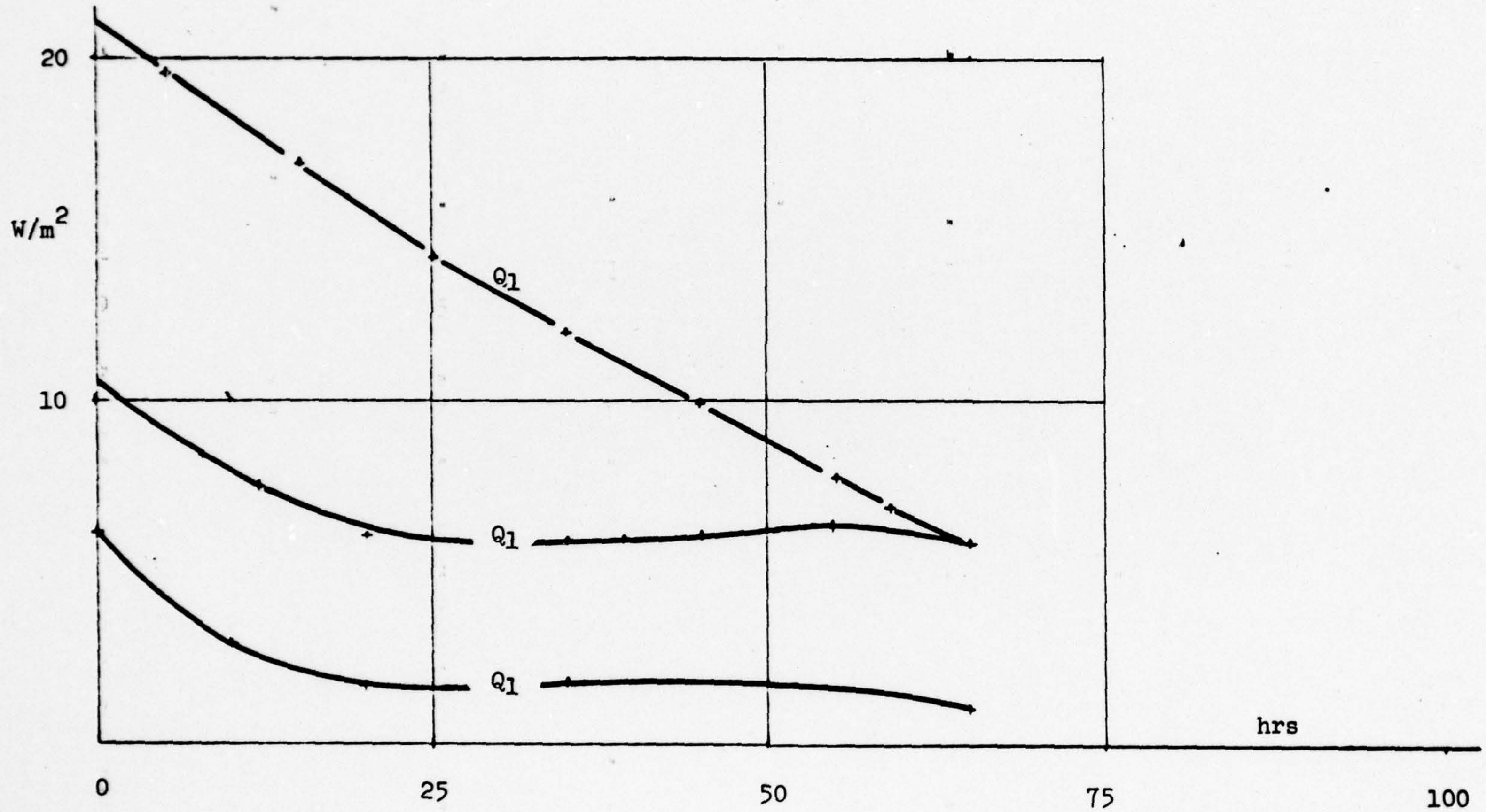


Figure 5. Evaporation heat transfer on the roof after rain.
Ballast: Elevated concrete pavers and insulation with open joints and channels.

Q = measured density of heat flow through wet roof, W/m^2

Q_1 = increase in density of heat flow due to moisture, W/m^2

Q_2 = heat equivalent to the measured rate of evaporation, W/m^2

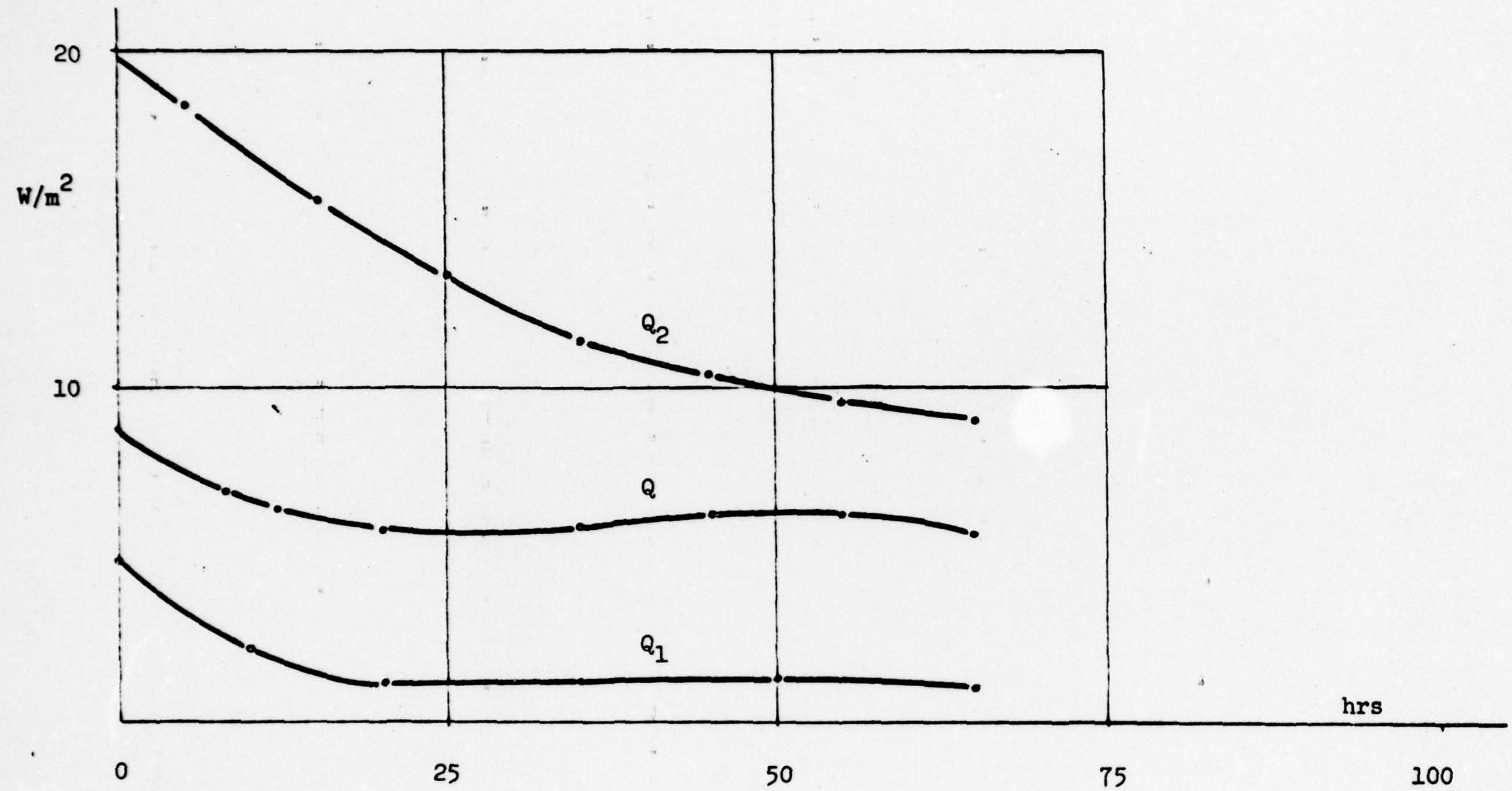


Figure 6. Evaporation heat transfer on the roof after rain.
Ballast: river gravel on filter screen, insulation with open joints and channels.

Q = measured density of heat flow through wet roof, W/m^2
Q_1 = increase in density of heat flow due to moisture, W/m^2
Q_2 = heat equivalent to the measured rate of evaporation, W/m^2

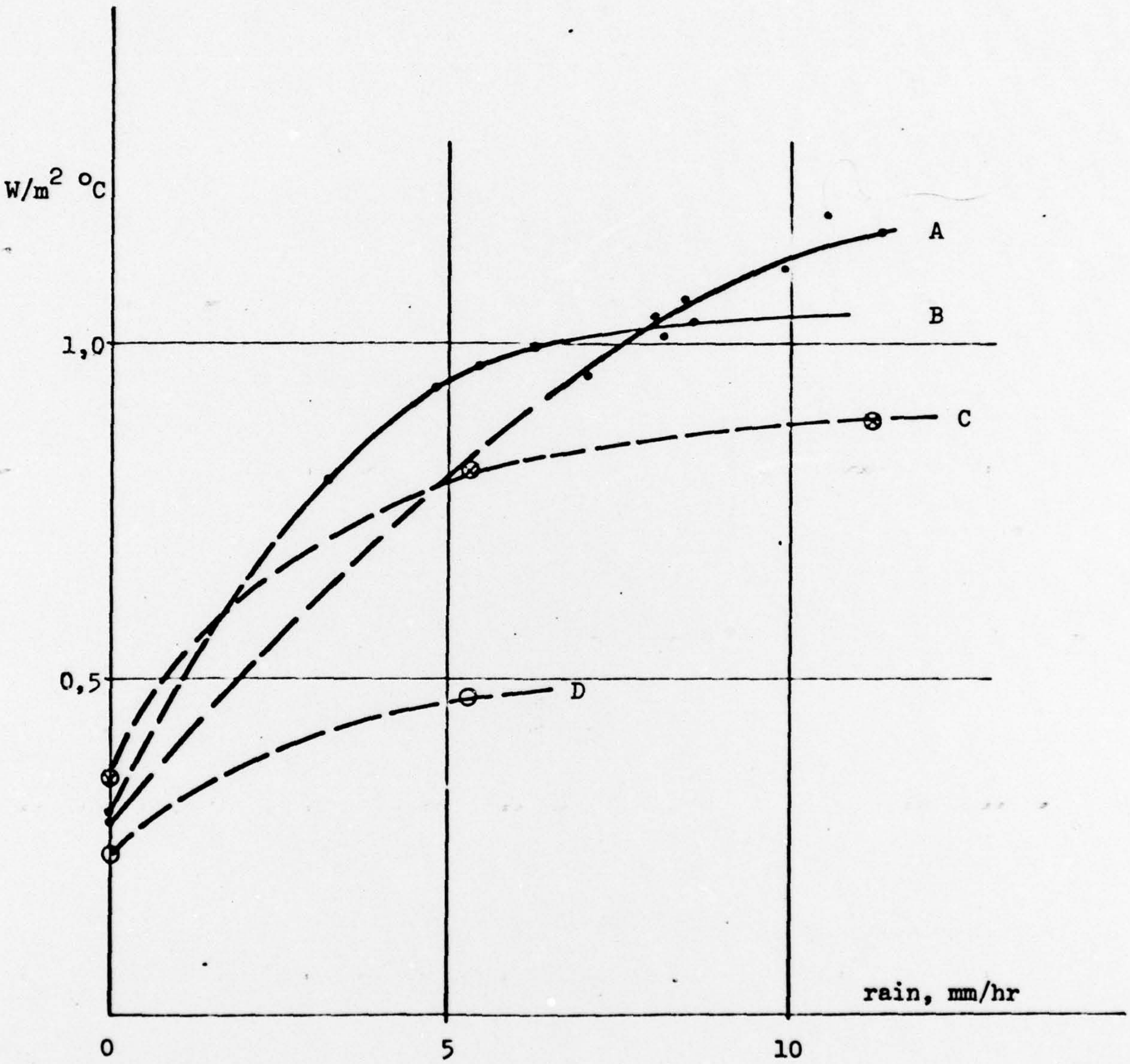


Figure 7. Heat transmittance vs. rain intensity.
Ballast: Concrete pavers.

A = tight joint
B = open joints
C = open joints and channels and elevated pavers
D = insulation added on underside

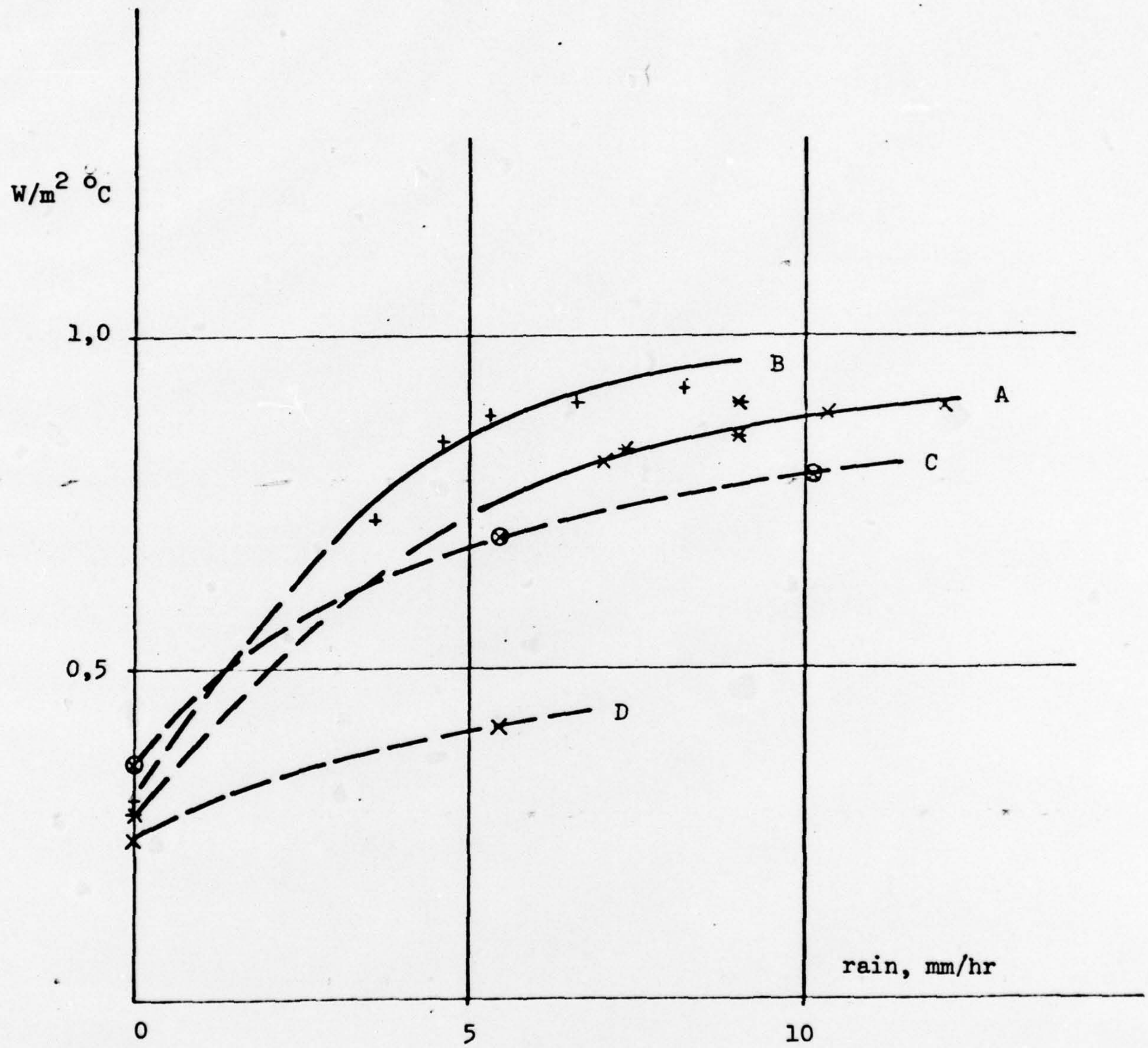


Figure 8. Heat transmittance vs. intensity.
Ballast: River gravel.

A = tight joint
B = open joints, filter screen on top of insulation.
C = open joints and cahnnels, filter screen on top of insulation
D = insulation added on underside

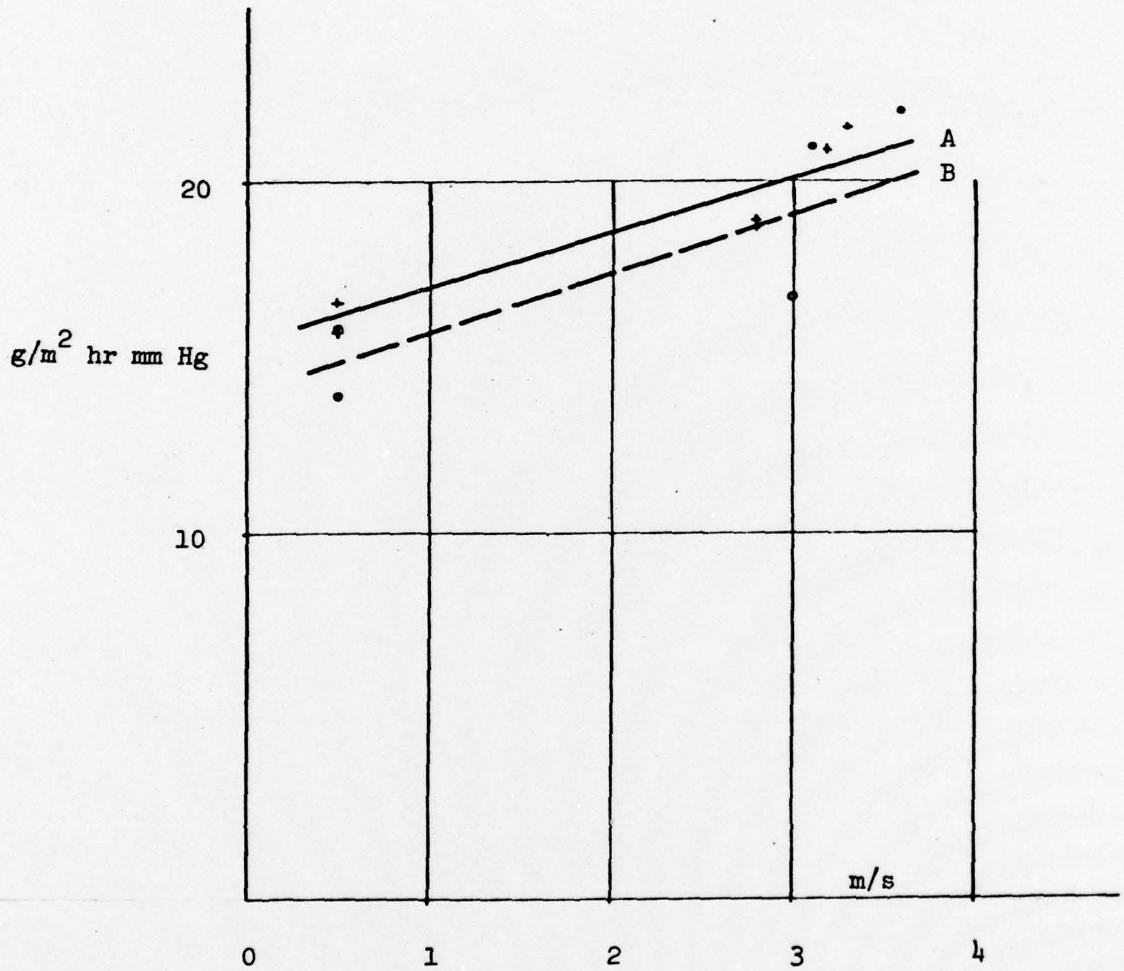


Figure 9. Average evaporation coefficient v.s. wind speed. The first 24 hrs after rain. Vapour pressure difference is between conditions at the membrane and in the moving air.

A = concrete pavers directly on insulation with tight joints

B = river gravel " " " " " "

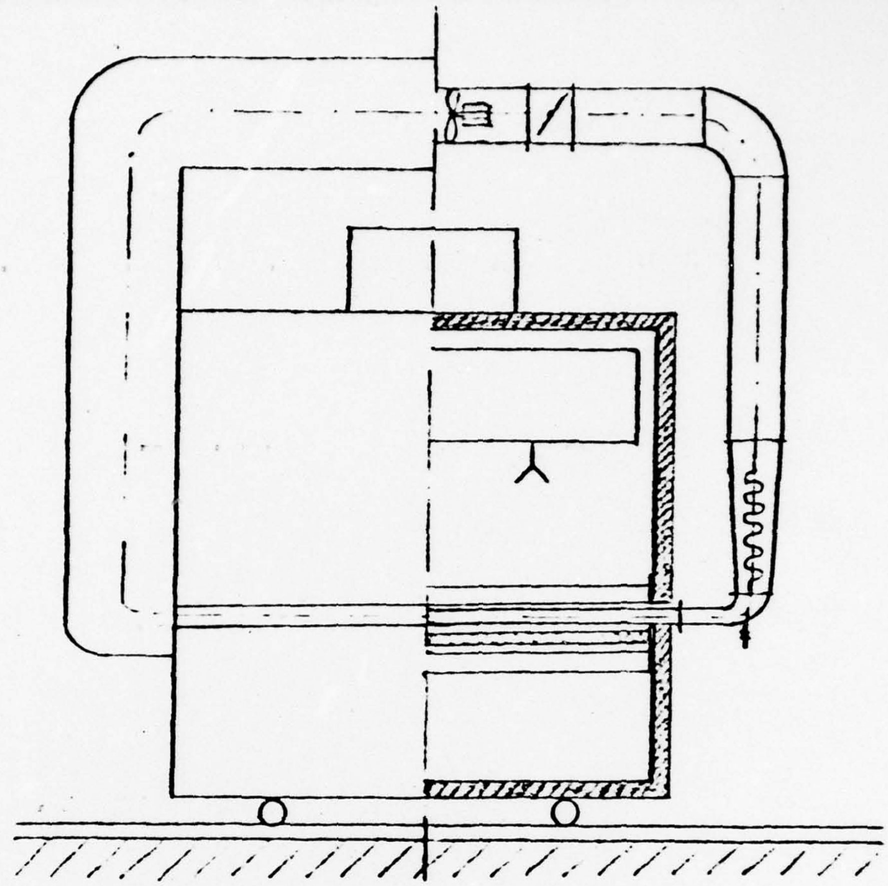
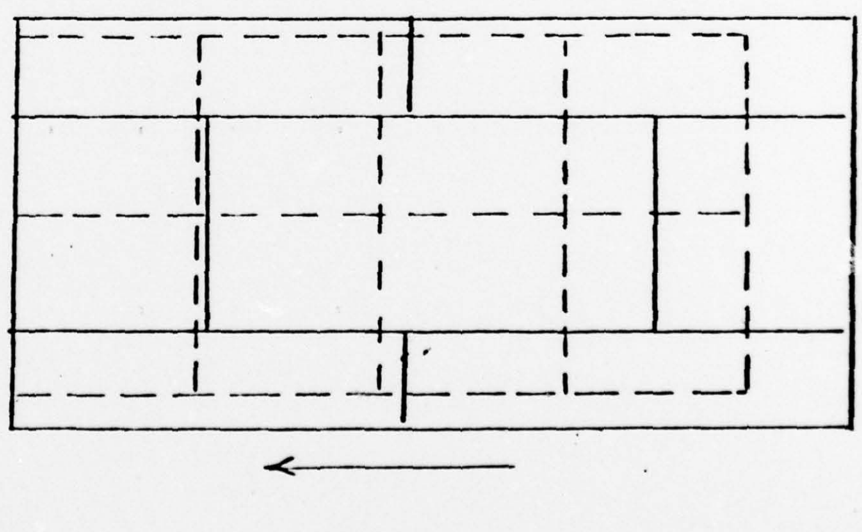


Figure 10. Roof test apparatus (scale 1:40).
Below: Joint pattern (1:2, whole line).
Position of heat flow meters (broken line).



Slope to drain

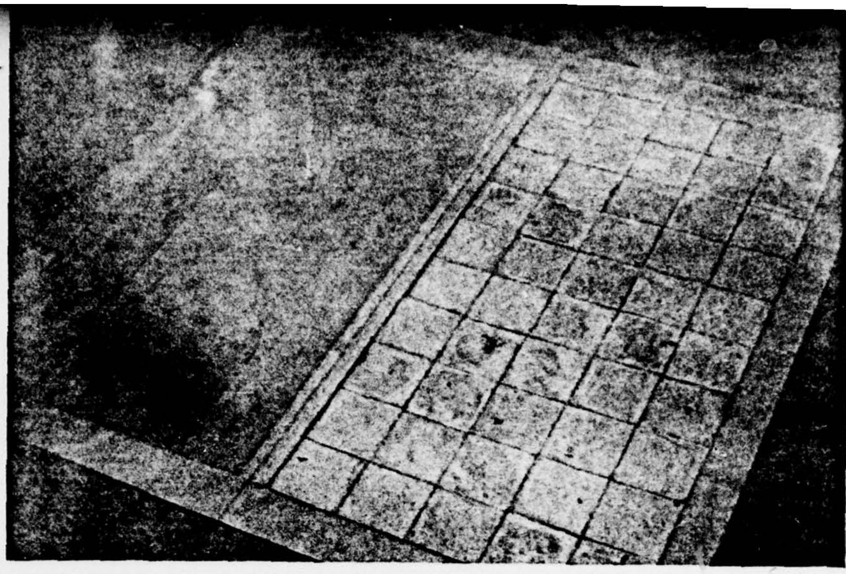


Figure 11

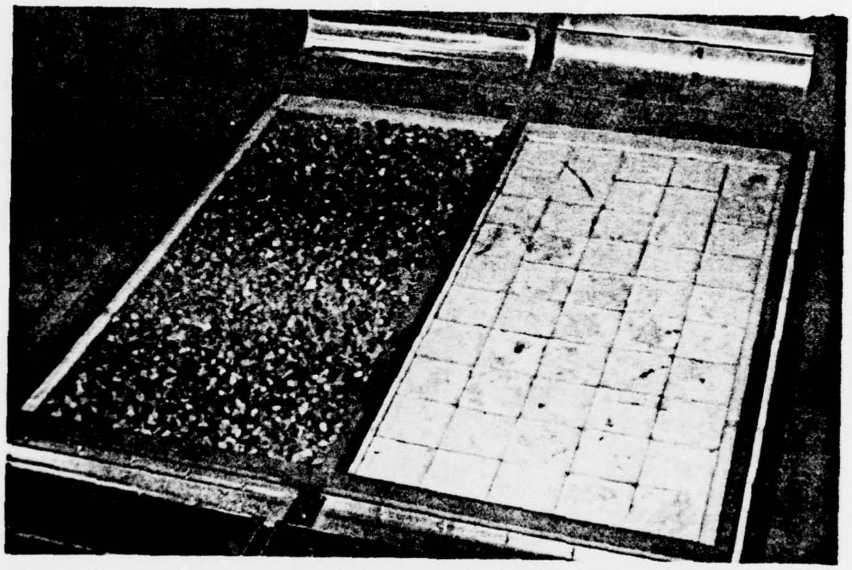


Figure 12

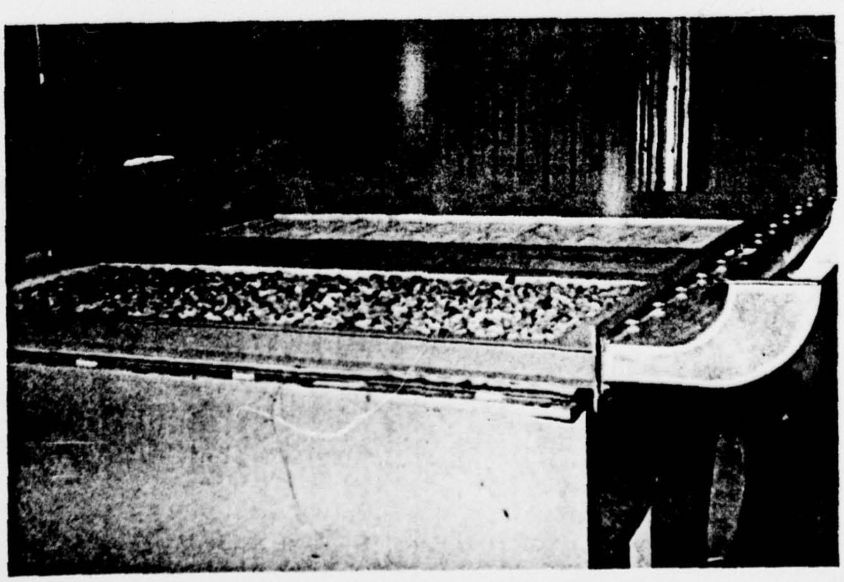


Figure 13

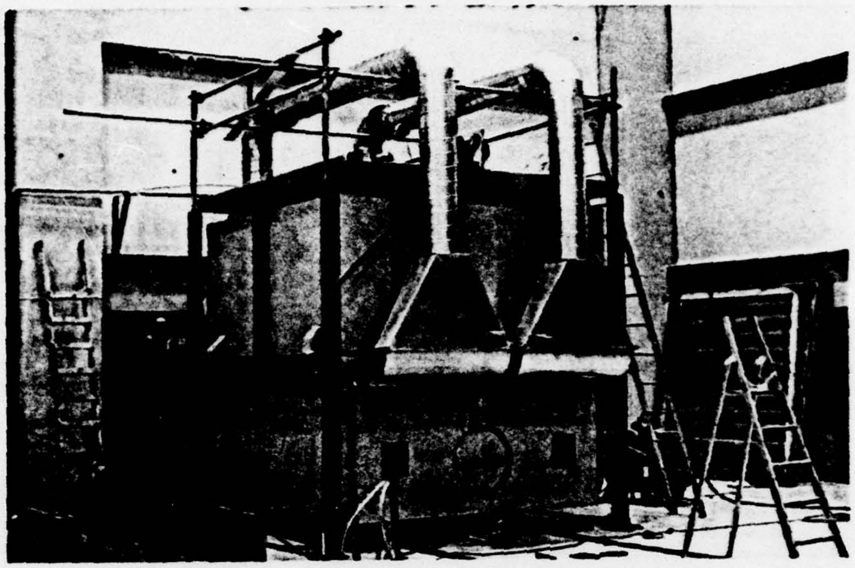


Figure 14

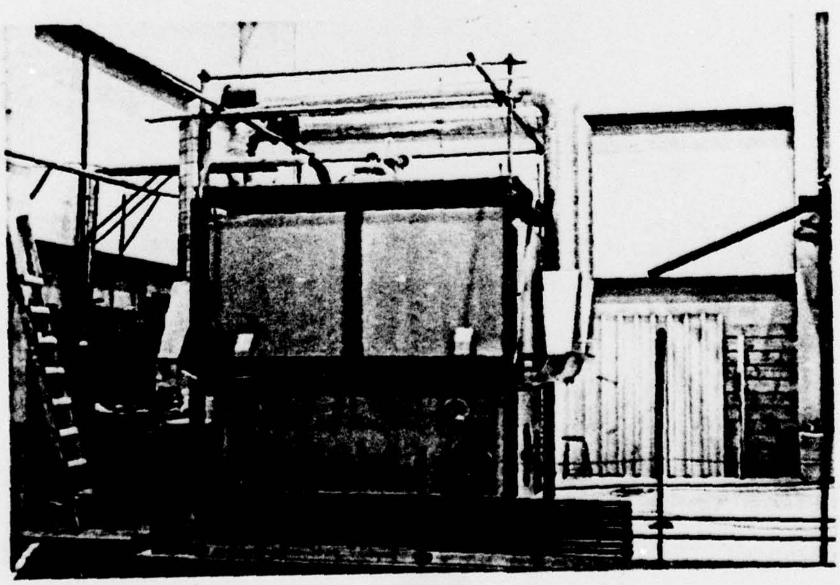


Figure 15

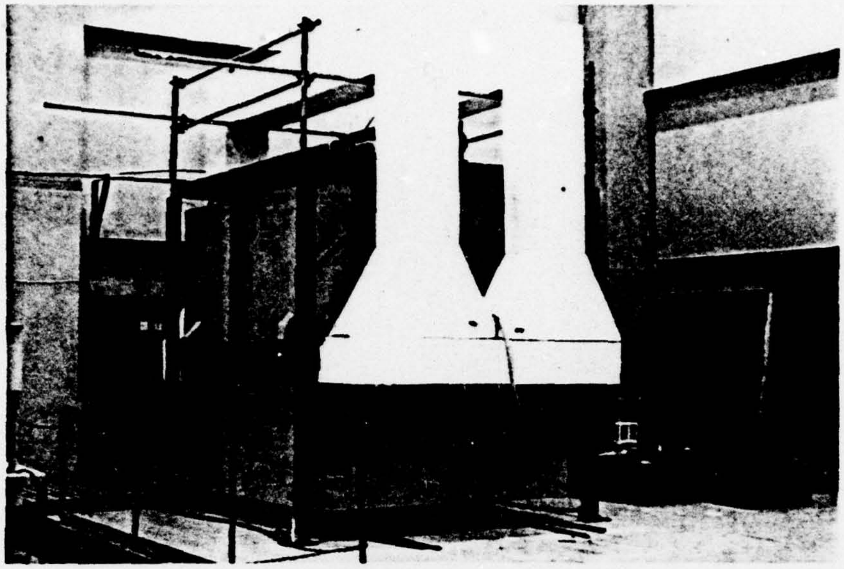


Figure 16

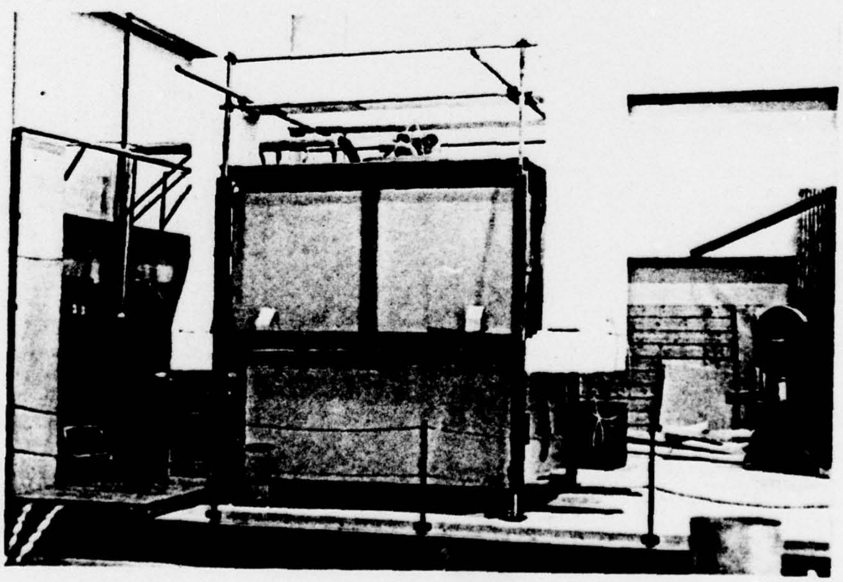


Figure 17